Atmospheric Pollutants and Trace Gases

Ammonia Emissions from Swine Houses in the Southeastern United States

Lowry A. Harper,* Ron R. Sharpe, and John D. Simmons

ABSTRACT

Ammonia (NH_3) from confined animal feeding operations is emitted from several sources including lagoons, field applications, and houses. This paper presents studies that were conducted to evaluate NH_3 emissions from swine finisher and sow animal houses in the southeastern USA. Management and climate variables including animal weight, feed consumption, housing gutter water temperature, total time fans operated per day, house air temperature, house ambient NH_3 concentration, and animal numbers were measured to determine their individual and combined effect on NH_3 emissions. Ammonia emissions varied on daily and seasonal bases with higher emissions during warmer periods. For finishers, the summertime housing emissions on a per-animal basis were 2.4 times higher than wintertime (7.0 vs. 3.3 g NH_3 animal^{-1} d^{-1}) or 3.2 times higher when compared on an animal unit (AU) basis (1 AU = 500 kg) because of climate and animal size differences between measurement periods. For summertime, the emission factor for the finishing pigs was 7.8 times higher than for sows on an animal basis and 25.6 times higher on an AU basis. Simple models were developed for housing emissions based on (i) all measured factors that were independent of each other and (ii) on three commonly measured management factors. The two models explained 97 and 64%, respectively, of variations in emissions. Ammonia emissions were found to be somewhat less than other studies on the same type housing due to more representative housing concentration measurements and calibration of exhaust fans; thus, emission factors for these type houses will be less than previously thought.

Ammonia is ubiquitous and is the major atmospheric alkaline component that neutralizes acid gases produced by burning fossil fuels. The neutralization process produces ammonium (NH_4^+), which is a major component of atmospheric aerosols (particulate matter) and rainfall (Asman, 1994). Wet and dry deposition, whether from agriculture, industry, or transportation, may exacerbate soil acidification (van der Molen et al., 1990) and possible plant nutrient imbalances in natural ecosystems. Additionally, many natural systems such as forest and heath are adapted to low nutrient conditions (Nilsson and Grennfelt, 1988) and when excessive quantities of nitrogen (N) are deposited onto the landscape, nitrophilous species become better competitors. However, in cropping systems, atmospheric NH_3 and NH_4^+ may be beneficial by adding N during critical times of the day (Harper et al., 1987) and during periods of soil N deficiency (Sharpe et al., 1988; Harper et al., 1996). Crop canopies may also remove significant quantities of NH_3 released to the atmosphere from nearby sources (Harper and Sharpe, 1995; Harper et al., 1996; Bussink et al., 1996; Sharpe and Harper, 2002).

Concentrated livestock production can be a significant source of NH_3 emissions to the atmosphere in a relatively small geographic area. Adverse effects may be due to the direct and indirect effects of NH_3 (which has a shorter residence time of hours) and/or NH_4^+ aerosols of nitrate (NO_3^-) and sulfate (SO_4^{2-}), which may have a residence time of 5 to 9 d (Crutzen, 1983). Early estimates (Hatfield et al., 1993) suggested that 89 to 90% of the N input to anaerobic lagoons is lost to the atmosphere through NH_3 volatilization. These estimates represent about 60% of the total feed N input into the farm operation. Current estimates in North Carolina (Doorn et al., 2002) suggest that 36% of the total N going into confined animal feeding operations (CAFOs) in the state is volatilized as NH_3 gas from all sources including lagoons, houses, and field applications. However, other studies in the North Carolina and Georgia Coastal Plains region of the USA (Harper and Sharpe, 1998; Harper et al., 2004) have shown that lagoons emit significantly less NH_3 than previously thought. Harper et al. (2004) found in a highly measured swine production operation that about 5% of the N going into the operation as feed left the lagoon as volatile NH_3 and another 1% from field application of waste effluent. Much of the N (about 43% of input feed) that entered into lagoons was found to be denitrified to N_2 (Harper and Sharpe, 1998; Harper et al., 2000, 2004) by microbial and/or chemical (Van Cleemput, 1998) denitrification. Another source of NH_3 emissions that has not been comprehensively measured is emissions from animal production houses. The purpose of this research was to evaluate NH_3 swine confinement housing emissions and

L.A. Harper and R.R. Sharpe, Southern Piedmont Conservation Research Unit, USDA-ARS-JPCSNRCC, 1420 Experiment Station Road, Watkinsville, GA 30677. J.D. Simmons, Poultry Research Unit, USDA-ARS, 606 Spring Street, Starkville, MS 39759. Contribution from the USDA-ARS-JPCNRCC, USDA-ARS Poultry Research Unit, and University of Georgia Agricultural Experiment Station. Received 30 Dec. 2002. *Corresponding author (lharper@uga.edu).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: AU, animal unit (1 AU = 500 kg); DOY, day of year; FF, farrow-to-finish; FW, farrow-to-wean.

Table 1. Management characteristics for the swine production units.

Measurement period	Farm	Management type	Animal number	Animal average weight	Feed consumption
			animals house^{-1}	kg animal^{-1}	kg animal^{-1} d^{-1}
11–16 February	10	farrow to finish	779	90.8	2.2
2–6 February	20	farrow to wean	886	208.8	2.2
22–28 July	10	farrow to finish (#9)	873	56.8	1.6
28–31 July	10	farrow to finish (#8)	904	62.6	1.4
8–18 August	20	farrow to wean	884	208.8	1.9

determine the amount of N as a fraction of feed input that leaves the farm system.

MATERIALS AND METHODS

The swine production houses described in this paper were "farrow-to-finish" (FF) and "farrow-to-wean" (FW) units at different locations in the Coastal Plains of North Carolina. The FF farm contained about 1200 sows and boars, 1400 nursing pigs, and 7500 finishers. The finishers, pigs being grown for market, ranged in size from 20 to 120 kg. Both of the houses measured at the FF farm contained finishing pigs only. The FW farm contained sows, boars, and nursing pigs. The house measured at the FW farm contained 886 sows. Table 1 presents management and facility characteristics for the houses. The FF houses were "flush"-type with recycled water from the lagoon used for flushing the gutters beneath the slatted floors. Effluent from the lagoon was pumped to flush tanks and every four hours two of the four gutters were flushed. The gutters had a 0.5% slope representing a 0.30- to 0.41-m water depth from entrance to exit to remove manure and urine during the flush cycle. The water depth was 0.30 m from the slat flooring. Four hours later the other two were flushed. The FW house used a "pull-plug," pit-recharge system beneath the slatted floors with a cycle time of about one week between drain and recharge. Two houses were instrumented at the FF farm with sensors to determine cycling of the individual forced-ventilation fans. Closed-path, tunable diode laser spectrometers (Edwards et al., 1994; Dias et al., 1996) (Trace Gas Analyzer System; Campbell Scientific, Logan, UT) were used to measure NH_3 and methane (CH_4) concentration differences between the intake and exhaust points of the houses. Measurements of CH_4 emissions were previously reported by Sharpe et al. (2001). Inside NH_3 concentrations were measured about 10 m from the exhaust fans to avoid variable air trajectories under different fan-on conditions. Ammonia concentrations were measured 10 times per second and differential concentrations (differences between the incoming and exiting air masses) were calculated every minute. Ambient temperature inside the houses and water temperature of the waste pits were measured with recording temperature sensors (WTA08; Onset Computer Corp., Bourne, MA). A portable fan airflow measurement system was mounted to each fan to measure total volumetric flow rate of the ventilation fans (Simmons et al., 1999) for fan efficiency evaluation. Fan flow rates are affected by maintenance, age of the fan, and the interference of flow rates by other fans nearby [reduced air pressure and interference of flow trajectories (Simmons et al., 1999)]. Each fan was measured to determine its efficiency, which varied slightly from the rated capacity due to aging and the number of fans operating. Fan efficiencies were measured for all the fans in each building independently and in combination sequence, which might occur due to the programmed sequence of all other fans. The fans ranged in efficiency from 82 to 98% depending upon the individual fan and the number and sequence of fans on at any time. Fan efficiencies were then applied to fans during the studies. Individual cup anemometers were used to determine when individual fans were operating. Two seasons of NH_3 emissions measurements were made during the annual climatic extremes, winter (11–16 Feb. 1998) and summer (22–31 July 1998) for the FF houses and 8 to 18 Aug. 1998 for the FW house.

A schedule of five to eight days of 24-h data collection periods were made throughout the winter and summer measurement seasons. Emissions were calculated from the trace-gas differentials of incoming and exhausting air and the exhausted air volumes produced by the fans. Fans were controlled by timing and/or temperature sensors to (i) maintain acceptable concentrations of NH_3 in the houses and (ii) maintain acceptable temperature levels. The NH_3 control was the dominant control with intermittent cycling (fan on approximately 8.5 min and off approximately 3.5 min) and inside temperatures were controlled by increasing numbers and sizes of fans operating.

The equation used to calculate NH_3 flux was:

$$NH_3 \text{ emissions (g min}^{-1}) = \Delta NH_3 \text{ (g m}^{-3}) \times \text{fan capacity (m}^3 \text{ min}^{-1}) \times \text{fan efficiency} \quad [1]$$

The sum of NH_3 emission rates from each fan equaled total flux from the house.

Calculations of NH_3 flux from the houses are based on the assumption that all emissions are through the exhaust fans at the end of the houses. This assumption may result in an underestimation of total flux during the winter period when fans were intermittently on. However, the underestimation is probably minimal because even during winter, fans operated a specified percentage of time to maintain NH_3 concentrations in the houses at an acceptable concentration. The FF houses had a set of five fans in the east end of the house. Fans 1, 3, and 5 had a rated capacity of 650 m^3 air min^{-1} and fans 2 and 4 had a capacity of 310 m^3 air min^{-1}. The FW house had six fans with rated capacities of 650 m^3 air min^{-1}.

RESULTS AND DISCUSSION

Differential NH_3 concentrations between the entrance (local ambient concentration) and the fan exit varied between seasons and production types. Figure 1 gives a trace of fan activity for a FF house and NH_3 differential concentrations between outside and inside the house. Outside ambient concentrations varied between 0.1 and 2 μg NH_3 g^{-1} depending on if the wind direction was from the forested areas nearby or from the lagoons or other buildings. Measurements from Day of Year (DOY) 28.9 to 29.0 in Fig. 1 showed the simplest type response in concentration variation to fan activity with only one fan cycling. The variation in NH_3 differential showed that when a fan turned on, the NH_3 concentration decreased quickly, but then gradually increased to a concentration approaching that of when the fans were off. We think that when a fan (or fans) was actuated, air initially was exchanged only from the house interior, whereas when the fan remained on for an extended period, air from the gutters mixed into the inte-

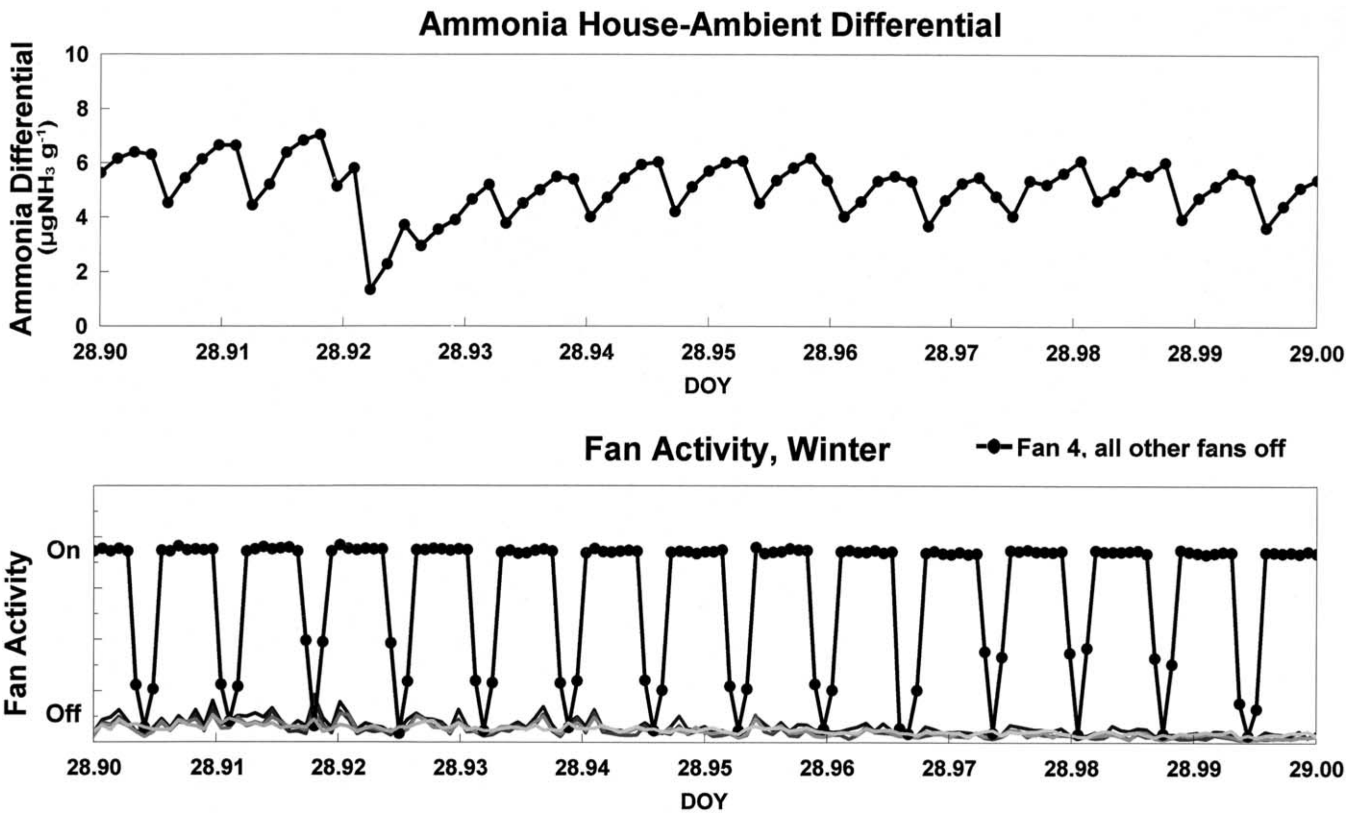

Fig. 1. The effect of wintertime fan activity on inside–outside house NH_3 differential concentrations. Fan status (on–off) was determined by measuring windspeed through the fans. The variability in lines at the off status are indicative of outside turbulence affecting the anemometers.

rior of the house increasing the interior concentration. Gutter fans in many types of FW houses (for smaller animals) are used to avoid mixing gutter gases into the house interior. Increased fan activity (summertime conditions, Fig. 2) did result in decreased house NH_3 concentrations with a seasonal decrease from 7.0 μg NH_3 kg^{-1} in winter to 3.3 μg NH_3 kg^{-1} in summer. Inside-house ambient NH_3 concentrations during wintertime and summertime were similar in magnitude (Fig. 2 and 3) when the fans were off in winter and the minimum number of fans on in summer. However, when the fans (or more fans) cycled on, the concentrations dropped quickly. Under summertime conditions the inside–outside differential can be seen to be generally a function of when the most fans (and their respective sizes) are on or off (Fig. 2).

Gutter water temperature during the measurement periods in winter ranged between 14 and 16°C due to the heat capacity of the building and soil surrounding the gutter, except for a short period after the gutter was flushed with lagoon effluent. The gutter temperature, measured 0.1 m above the gutter floor in the effluent, decreased about 4°C in winter for about 45 min. In summer, the gutter temperature increased about 5 to 7°C because of the warm lagoon effluent flush water.

Measured finishing housing emissions during the winter ranged from no emissions (when all fans were off) to a short-term maximum of about 7.5 g NH_3 min^{-1} $house^{-1}$ (Fig. 3). The average seasonal winter emission was 2.57 kg NH_3 d^{-1} $house^{-1}$ (3.3 g NH_3 $animal^{-1}$ d^{-1} or 18.1 g NH_3 AU^{-1} d^{-1}) (an animal unit, AU, is based on an animal weight of 500 kg) or 5.7% of feed N input to the farm. Summer finishing house emissions ranged from a minimum of 3 kg NH_3 d^{-1} $house^{-1}$ (since fans were on continuously for temperature control) to as high as 14 kg NH_3 d^{-1} (Fig. 2) giving a summer seasonal average of 6.25 kg NH_3 d^{-1} $house^{-1}$ (7.0 g NH_3 $animal^{-1}$ d^{-1} or 58.9 g NH_3 AU^{-1} d^{-1}) or 8.2% of feed N input to the farm. Ammonia emissions are generally a function of the physical and chemical parameters of solution NH_4^+ concentration, pH, and temperature, and air turbulence to remove NH_3 from the water–air boundary layer. Summertime housing emissions were larger (2.4 times) than wintertime, due to higher gutter water temperature and inside turbulence and air exchange. There was no emissions effect due to winter and summer lagoon NH_4^+ and pH (used for flush water) since they were not significantly different between seasons (Harper et al., 2004). Gutter NH_4^+ and pH were not measured because the houses were flushed every four hours. On a per-AU basis, NH_3 emissions were 3.2 times higher in summer than winter due to climate and animal size differences for the respective seasons. Annual emissions for the FF farm were 14 347.4 kg N yr^{-1} representing 7.3% of feed input to the farm.

Summertime sow house emissions ranged from no emissions to a maximum of 3.5 g NH_3 min^{-1} $house^{-1}$. The seasonal average summertime emission was 0.80 kg NH_3 d^{-1} $house^{-1}$ (0.9 g NH_3 $animal^{-1}$ d^{-1} or 2.09 kg NH_3 AU^{-1} d^{-1}) or 1.8% of feed N input to the farm.

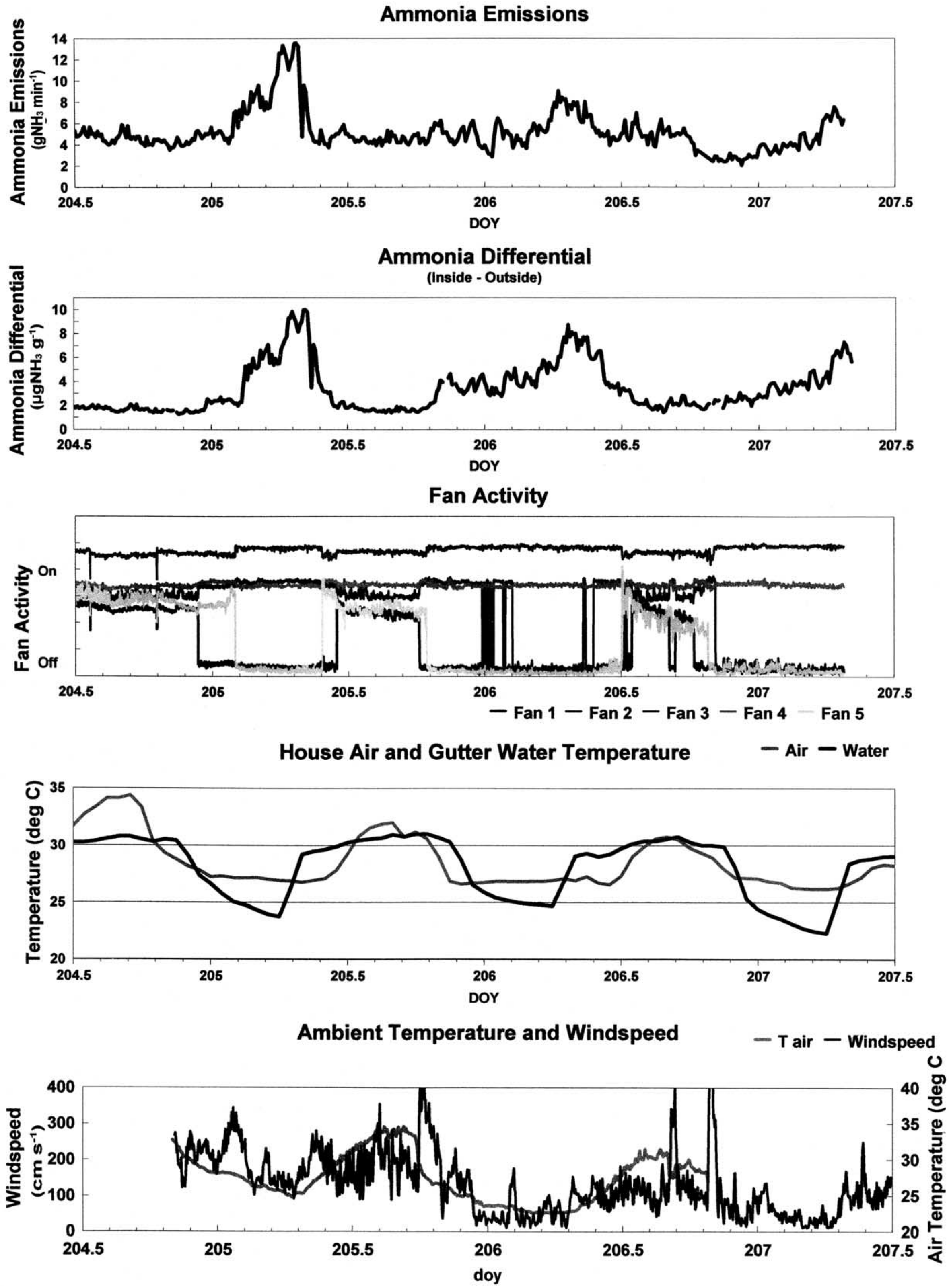

Fig. 2. Summertime 24-h NH_3 emissions and concentrations in a swine finishing house in response to climate and fan activity. Fan status (on–off) was determined by measuring windspeed through the fans. Differences in the magnitude of the fan windspeeds result from different fan efficiencies and fan sizes.

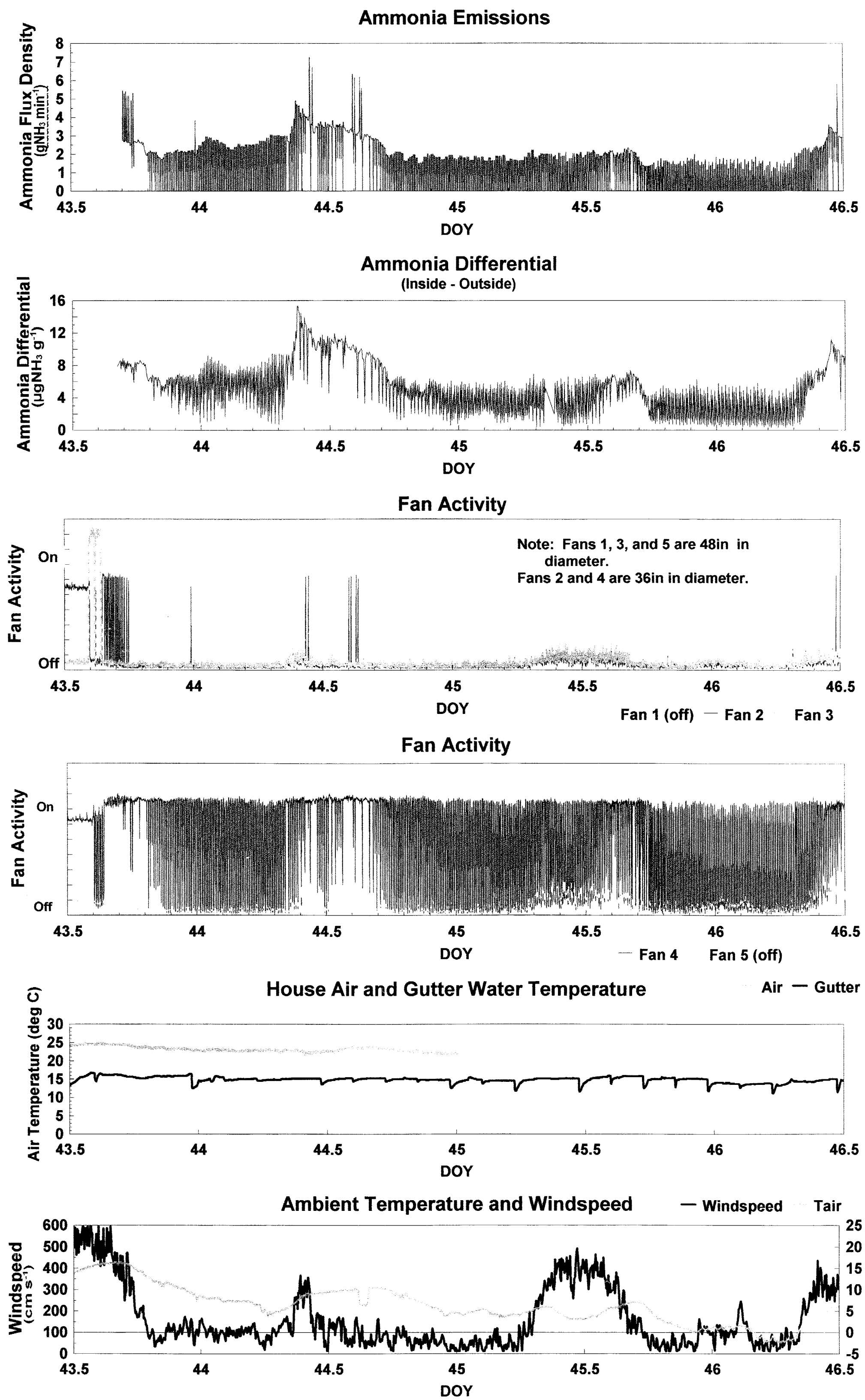

Fig. 3. Wintertime 24-h NH_3 emissions and concentrations in a swine finishing house in response to climate and fan activity. Fan status (on–off) was determined by measuring windspeed through the fans. Differences in the magnitude of the fan windspeeds result from different fan efficiencies and fan sizes.

Table 2. Comparison of annualized emission factors on a per-animal basis for finishing operations.

Location	Emission factor	Type	Reference
	kg NH_3 animal^{-1} yr^{-1}		
U.S. Midwest	4.68	house + gutter fans, summer only	Parbst et al. (2000)
North Carolina, Farm 10	4.81	daylight measurement only, summer only	Harris et al. (2001)
North Carolina, Farm 10	3.36	daylight measurement only, summer only	Harris and Thompson (1998)
North Carolina, Farm 10	2.57	total daily measurement, summer only	this study
North Carolina, Farm 10	3.05	daylight measurement only, annual	Harris and Thompson (1998)
North Carolina, Farm 10	1.89	total daily measurement, annual	this study

Summertime emissions of the finishing houses were 7.8 times higher than for sows and 25.6 times higher on an AU basis. Wintertime emissions are not available for the sows, but an annual estimate of the FW house emissions, based on summertime emissions, was less than 1% of feed N emitted to the atmosphere as NH_3.

Studies by Harris and Thompson (1998) on the same houses suggested little seasonal variation existed between winter and summer NH_3 emission rates (7.5 g NH_3 animal^{-1} d^{-1} in winter and 9.2 g NH_3 animal^{-1} d^{-1} in summer) because the animals were kept in a reasonably constant environment with little stress from outside environmental factors. The differences between studies are probably due to the fact that the measurements of Harris and Thompson (1998) were determined during daylight periods and extrapolated to an entire day. Also, because their concentrations were measured outside about 10 m from the exhaust fans it is possible that some of the plumes may have been entrained to the inlets, providing a significant increase in background or incoming NH_3 concentration.

Comparison of summertime emissions on an annualized basis from several studies show considerable differences in emissions (Table 2). Although the study of Harris and Thompson (1998) and this study were on the same farm, the differences may be attributable to measurement period and location. The difference between the results of Parbst et al. (2000) and the current study may be due to the use of gutter fans (with an associated increased turbulence in the pit area) to minimize house NH_3 concentrations in the Parbst et al. (2000) study. Table 2 also exemplifies the difference between the use of annualized data taken only in one season compared with annual measurements since ambient climatic conditions will affect emissions even though the housing climate is regulated.

Seasonal differences between animal house types are evident in Fig. 2 and 3. Ammonia concentrations in the houses were slightly higher during winter than summer because of decreased air exchange for heat conservation. During winter (Fig. 3) a slight daily variation in house concentrations and emissions occurred due to the duration of time the primary fan, which was programmed to cycle for NH_3 removal, was on. As long as the cycling was constant (e.g., DOY 45.8–46.3), inside NH_3 concentrations and emissions followed the fan cycling. However, when inside ambient temperature required the fan to stay on for longer periods, the NH_3 concentrations increased (except DOY 45.6) with a slight increase in emissions. Similarly, when the primary fan remained on for most of the time or a secondary fan came on, NH_3 concentrations increased significantly (e.g., DOY 44.3–44.7) along with an increase in emissions. It is interesting that when the primary fan remained on for longer periods, the house concentrations did not drop similar to the periods when the fan was on intermittently. We think that when the fan remained on for longer periods, turbulence structure in the house was larger and pulled NH_3 from the pit area. This phenomenon was observed throughout the winter season measurements. Many types of swine houses have gutter fans to reduce NH_3 concentrations inside the house, particularly when the animals are small. Initiation of a secondary fan increased emissions considerably (e.g., DOY 44.6). During summer, there were some fans on continuously and the house concentrations were generally a function of the number of fans operating. There were increased NH_3 concentrations and emissions on a daily basis around sunup each day. Fan activity did not correlate with the spikes and we think the increases were due to animal activity (wake-up and/or feeding times).

Ammonia emissions of sows and finishers were quite different (Fig. 2 and 4). Concentrations during summer for the sows were much lower than finishers. During nighttime, the inside–outside concentration differentials for the sows approached zero and emissions were very small. The emission factor for finishers was 7.8 times higher than sows. Seasonal average emissions of sows were 0.80 kg NH_3 d^{-1} house^{-1} (0.9 g NH_3 animal^{-1} d^{-1} or 2.30 kg NH_3 AU^{-1} yr^{-1}). There was a distinct daily variation in the sow house similar to the finishers with increases in concentrations and emissions beginning about sunup and feeding time. We think that the much greater concentrations in the house during daytime were due also to increased turbulence when all the fans were running.

Table 3 presents average daily information on measurements and input production data for the finisher and sow houses for the two seasons of measurement. Due to equipment malfunction, winter data for the sow houses are not available. There were variations in seasonal daily averages due mainly to change in ambient microclimate. Multiple regression analysis suggested that animal size, total duration when fans were operating, and NH_4^+ content of the input flush water were the dominant factors affecting house emissions. A regression model (number of observations = 21 daily average values over the summer and winter periods, df = 16) estimating individual housing emissions based on these management and measured factors explained 97% of the variability in emissions:

$$F_{NH3} = (-0.6955 \times AW) + (4.42 \times 10^{-5} \times t_f) - (0.1923 \times NH_4^+) + (70.0802 \times C_f) + (0.7931 \times T_{gw}) \quad [2]$$

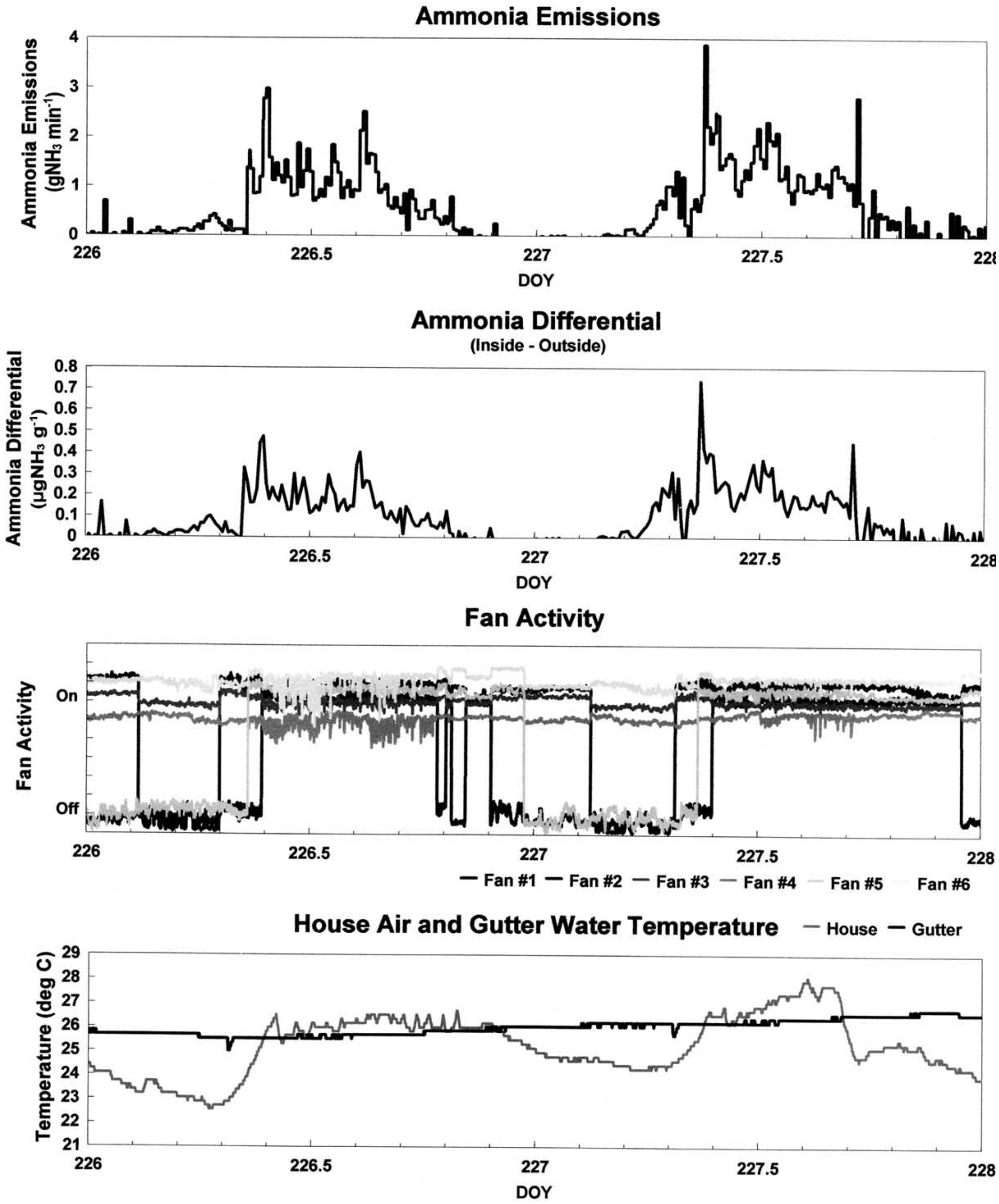

Fig. 4. Summertime diurnal NH_3 emissions and concentrations in a swine sow house in response to climate and fan activity. Fan status (on–off) was determined by measuring windspeed through the fans. Differences in the magnitude of the fan windspeeds result from different fan efficiencies and fan sizes.

where F_{NH3} is the NH_3 housing emission rate in kg NH_3 d^{-1}, AW is the average animal weight in kg animal^{-1}, t_f is the total time all fans were operating per day (min d^{-1} for all fans), NH_4^+ is the ammonium content of input flush water in μg g^{-1}, C_f is feed consumption in kg animal^{-1} d^{-1}, and T_{gw} is the gutter water temperature (°C). The valid ranges of input values for the statistical relationships are AW = 90 to 300 kg animal^{-1}, t_f = 650 to 15 000 min d^{-1} for all fans, NH_4^+ = 160 to 550 μg g^{-1}, C_f = 1.5 to 2.2 kg animal^{-1} d^{-1}, and T_{gw} = 15 to 29°C. Individual coefficient standard errors for AW, t_f, NH_4^+, C_f, and T_{gw} were 0.0761, 6.46×10^{-5}, 0.0222, 7.9841, and 0.0650, respectively. A regression of common production and easily measured variables explained 64% of the variability in emissions. This simple predictive relationship, including input data for animal weight, gutter washwater NH_4^+ content, and feed consumption, is shown in Eq. [3]:

Table 3. Average daily information from finisher and sows houses in North Carolina.

Animal type	Day of year	Ammonia emissions	House ammonia concentration	Total time all fans on	House air temperature	Gutter water temperature	Animal numbers	Animal weight	Feed consumption
		kg NH_3 d^{-1}	μg NH_3 g^{-1}	min d^{-1}	°C		animals $house^{-1}$	kg $animal^{-1}$	kg $animal^{-1}$ d^{-1}
Finishers	28	1.654	14.4	1 039	23.1	15.1	779	90.8	2.24
Finishers	38	3.401	12.4	636	23.1	15.1	779	90.8	2.24
Finishers	44	3.310	8.7	1 168	23.2	15.1	779	90.8	2.24
Finishers	45	2.975	8.4	1 063	22.9	14.9	779	90.8	2.24
Finishers	46	1.489	5.5	829	23.1	14.9	779	90.8	2.24
Finishers	205	8.600	3.3	6 010	30.5	29.0	873	56.8	1.50
Finishers	206	7.460	3.7	4 632	28.4	28.4	873	56.8	1.50
Finishers	207	6.819	3.8	4 401	28.0	28.2	873	56.8	1.50
Finishers	208	6.972	4.3	3 890	27.4	26.9	873	56.8	1.50
Finishers	209	6.937	4.0	3 689	27.4	28.2	873	56.8	1.50
Finishers	210	7.443	3.6	4 641	27.4	27.7	873	56.8	1.50
Finishers	211	2.967	1.7	5 879	27.3	27.4	904	62.6	1.50
Finishers	212	2.819	1.9	5 883	27.3	27.8	904	62.6	1.50
Sows	221	0.636	0.5	14 400	26.2	26.3	884	196.6	1.91
Sows	222	0.660	0.5	12 872	25.5	26.2	884	196.6	1.91
Sows	223	0.598	0.5	14 277	24.9	24.9	884	196.6	1.91
Sows	225	1.312	0.5	14 400	24.9	24.9	884	196.6	1.91
Sows	226	0.324	0.1	10 706	25.0	25.0	884	196.6	1.91
Sows	227	1.054	0.1	9 124	25.5	25.5	884	196.6	1.91
Sows	228	1.226	0.1	9 124	26.1	26.1	884	196.6	1.91
Sows	229	0.586	0.1	5 568	26.3	26.3	884	196.6	1.91

$$F_{NH3} = (0.2065 \times AW) + (0.0723 \times NH_4^+) - (24.3307 \times C_f) \quad [3]$$

where number of observations = 21, df = 18, and the standard errors of the coefficients are 0.0520, 0.0156, and 6.0649, respectively.

CONCLUSIONS

Ammonia emissions were measured from finishing and sow housing under summertime and wintertime conditions. Emissions were found to be somewhat less than other studies on the same type housing due to total daily measurement, possibly more nearly representative inside housing NH_3 concentrations, actual calibration of fans, and totalization of individual fan operation during the measurement. Emissions from this type of animal house were also found to be somewhat less than similar emissions measurements made in the U.S. Midwest. However, this type of housing did not have pit fans to remove NH_3 from the gutters, a factor that would increase the turbulence in the gutter area causing higher emission rates for the same type animals. Regression models were developed to predict emissions from the houses and if all measured management and environmental independent factors were included in the model, 97% of the variability in emissions was explained. A simple regression model of commonly measured production factors explained 64% of the variability in emissions.

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